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Is the Glass Half Full or Half Empty?

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Big-bang nucleosynthesis is a scientific success story and a pillar of the standard hot big-bang cosmology. Or is it? Over the past year there has been a lively debate about just this. As befits the times, the debate has been carried out on the Los Alamos archive, at meetings and workshops, in coffee rooms, and occasionally in refereed journals. The paper by Fields, Kainulainen, Olive and Thomas [1] in the inaugural issue of *New Astronomy* is part of this debate.

First some history; in the 1940s Gamow and his collaborators put forth the idea that all the chemical elements could have been synthesized a few minutes after the big bang, provided it was a hot big bang. (As it turns out, Coulomb barriers prevent significant production of elements beyond mass eight.) In 1948 Gamow's colleagues Alpher and Herman used the yield of ^{4}He and heavier elements to predict the temperature of the Universe today and arrived at 5 K. It seems that only Fred Hoyle took this prediction seriously, and used it to argue against the big-bang model: A temperature of 5 K exceeds the 2.3 K upper limit inferred from the relative abundance of rotationally excited CN molecules in gas clouds in the Galaxy by Adams and McKellar in 1941. As it turns out, the Alpher-Herman prediction was high because of the value of the Hubble constant used and the assumption that baryons provide the critical density, and the Adams-McKellar temperature limit was low.

The rest of the story is well known. In the early 1960s, unaware of Gamow's work, Peebles repeated the calculations and convinced his Princeton colleagues Dicke, Roll, and Wilkinson to search for this microwave radiation. Before they could, down the road in Holmdel, NJ Penzias and Wilson made their serendipitous discovery of the Cosmic Background Radiation (CBR). The temperature of the CBR is now know to four significant figures, $T = (2.728 \pm 0.002)\,$K, thanks to the beautiful measurement by the FIRAS instrument on the COBE satellite [2]. Shortly after the discovery of the CBR, the first detailed calculations of big-bang nucleosynthesis were carried out by Peebles and by Wagoner, Fowler and Hoyle.

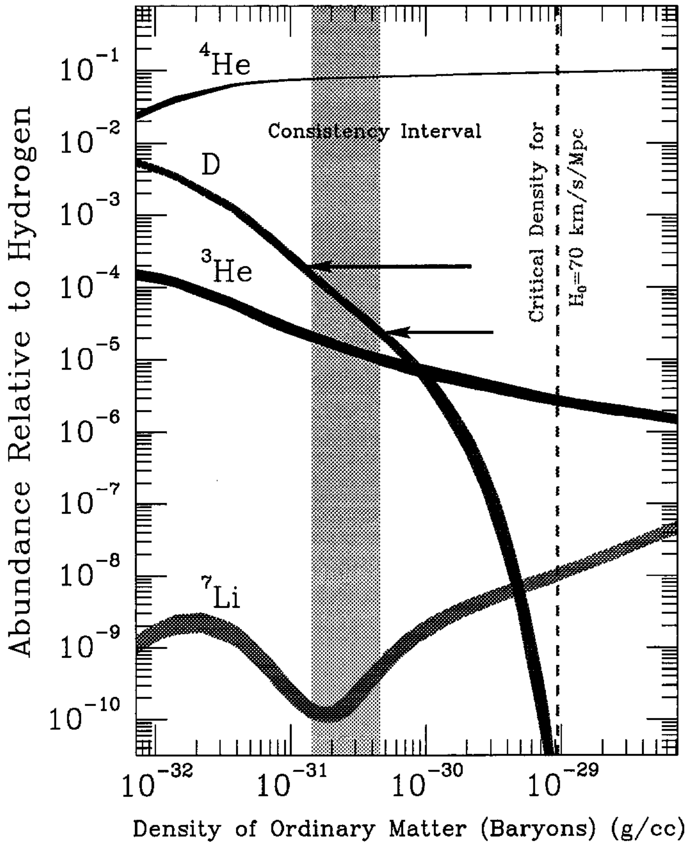

Figure 1: Big-bang production of the light elements; widths of the curves show the two-sigma theoretical uncertainty. The pre-debate consensus consistency interval is shown ($\rho_B = 1.5 \times 10^{-31}\,\mathrm{g\,cm^{-3}} - 4.5 \times 10^{-31}\,\mathrm{g\,cm^{-3}}$, or $\Omega_B h^2 = 0.008 - 0.024$). Arrows indicate the high and low deuterium detections.

Four light nuclei are produced in significant amounts – D, ^{3}He, ^{4}He and ^{7}Li – with the yields that depend upon the baryon density and input microphysics (nuclear cross sections and the number of light neutrino species). The yield of ^{4}He is large (by mass around 25%) and varies logarithmically with baryon density (Fig. 1). Establishing the existence of a large, primeval ^{4}He abundance was the first success of big-bang nucleosynthesis [3].

The yield of deuterium is much smaller, by number around 10^{-5} relative to H (Fig. 1); moreover, the deuteron is weakly bound and easily destroyed. However, in 1973 Reeves, Audouze, Fowler and Schramm [4] made the case for deuterium's cosmological utility: It cannot be made in significant amounts in the contemporary Universe – the mere presence of deuterium is evidence for the big bang – and the rapid decrease of its big-bang production with baryon density makes it a good "baryometer." The first determination of the cosmic deuterium abundance, indirectly in the solar wind by a foil placed on the moon by Apollo astronauts and in the local ISM by the Copernicus satellite, was the second success of big-bang nucleosynthesis. Further, by setting a lower limit to the primeval D abundance, it led to an upper limit to the baryon density, at most 10% of the critical density. To foreshadow, an actual determination – as opposed to a lower limit – of the primeval D abundance allows an accurate measure of the baryon density.

The ^{3}He and ^{7}Li stories are more complicated; both are produced and destroyed in the contemporary Universe. The abundance of ^{7}Li varies from greater than 10^{-9} relative to H in meteorites to less than 10^{-12} relative to H in some low-mass stars. In the early 1980s the Spites [5] announced that they had determined the primeval ^{7}Li abundance by measuring its abundance in the atmospheres of pop II halo stars. Their case hinged upon "the Spite plateau" – a leveling of the abundance with increasing stellar mass at a value around $(1.5 \pm 0.5) \times 10^{-10}$ relative to H. Lithium can be destroyed by convection; lower-mass stars have deeper convection zones; the leveling of the ^{7}Li abundance was indicative of the disappearance of convective ^{7}Li burning. The abundance measured by the Spites was consistent with the abundances of D and ^{4}He; success number three.

All stars produce ^{3}He by burning D even before they reach the main sequence; low-mass stars are believed to make additional ^{3}He and high-mass stars destroy most of their ^{3}He. Since the material in the ISM is either primeval or cycled through stars – mainly through low-mass stars since metal production by massive stars limits the amount of processing they can do – it has been argued that the sum of D + ^{3}He has not changed greatly. Based upon this argument, ^{3}He was brought into the fold in the early 1980s [6]; success number four.

Until a year ago most workers in the field would have agreed that the big-bang predictions for all four light nuclei are consistent with their measured abundances provided the baryon density is between $1.5\times10^{-31}\,\mathrm{g\,cm^{-3}}$ and $4.5\times10^{-31}\,\mathrm{g\,cm^{-3}}$ [7], corresponding to a fraction of critical density $\Omega_B \simeq (0.01-0.02)h^{-2}$ ($h = H_0/100\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$). This is the earliest test of the hot big bang and establishes a firm foundation for the exciting speculations about the Universe at even earlier times (e.g., inflation and cold dark matter). Accepting the success of the standard cosmology, this leads to the best determination of the density of ordinary matter as well as a stringent limit to the number of light neutrino species, $N_\nu < 4$ [8] (a prediction now confirmed by the high-precision LEP/SLC direct measurements based upon the width of the Z-boson).

The success as well as the importance of nucleosynthesis has spurred increased interest and more observations. The abundance of ^{7}Li (as well as ^{6}Li, B and Be) has now been measured in hundreds of old halo stars [9]; there are now high-precision measurements of the ^{4}He abundance in more than fifty metal-poor, extragalactic HII regions [10]. Within the past year the ^{3}He abundance has been measured in the local ISM for the first time [11], HST has accurately determined the D abundance in the local ISM [12], and a twenty-year old goal has been realized – detection of D in high redshift hydrogen clouds ($z \sim 2.5-4.7$) [13]. These new observations have made possible discussions – in some cases arguments – about the third significant figure in the primordial ^{4}He abundance, about the extent to which ^{7}Li may have been depleted in old halo stars, about whether or not low-mass stars preserve and produce additional ^{3}He, and perhaps most interestingly the value of the primeval D abundance.

There are three detections of the D Ly-α feature in the absorption spectra of high-redshift QSOs – two by Tytler and his colleagues [14] in clouds at redshifts $z = 2.5$ and $z = 3.57$ and one by Songaila and her colleagues [15] in a cloud at redshift $z = 3.32$; there are four other tentative detections. Both of Tytler's clouds give (D/H)$\simeq (2.4 \pm 0.3) \times 10^{-5}$, while Songaila's cloud gives a value that is about ten times larger, (D/H)$\simeq (2 \pm 0.4) \times 10^{-4}$. The Tytler value is at the extreme low end of the anticipated range, corresponding to the highest baryon density; the Songaila value is at the extreme high end of the anticipated range (in my book, this is success number five). Since a measurement of the primeval deuterium abundance pegs the baryon density very accurately much of the recent debate centers on it. Tytler et al suggest that the Songaila detection is due to a rogue hydrogen cloud fortuitously located to mimic D, while Songaila et al suggest that Tytler has underestimated the neutral hydrogen column and/or deuterium has been depleted in his clouds.

Fields and his colleagues [1] favor the high value of deuterium, which indicates a low baryon density $\rho_B \simeq 1.5 \times 10^{-31}\,\mathrm{g\,cm^{-3}}$ ($\Omega_B \simeq 0.01h^{-2}$), because the predicted ^{4}He and ^{7}Li abundances then nicely fit the observations. This interpretation makes the case for nonbaryonic dark matter ironclad since Ω_B can be at most a few percent and few would argue that Ω_0 can even be as small as 10%. The problem is explaining where all the deuterium went. In the ISM today, (D/H)$\simeq (1.6 \pm 0.1) \times 10^{-5}$, about a factor of ten smaller. Further, this, taken with Gloeckler and Geiss's measurement of ^{3}He in the local ISM today [11], implies (D+^{3}He)/H$\simeq (3.7 \pm 0.8) \times 10^{-5}$, a factor of five smaller than the primordial value. To accommodate this requires an efficient new way of destroying of ^{3}He – several have been suggested [16] – but even that is not an easy out. The value of D + ^{3}He deduced for the pre-solar nebula, which reflects the ISM 4.5 Gyr ago, is essentially identical, (D+^{3}He)/H$\simeq$ $(4.2 \pm 1) \times 10^{-5}$, suggesting that an efficient mechanism of destroying ^{3}He is not at work [17]. In any case, ^{3}He is a problem as the Gloeckler and Geiss's measurement of ^{3}He is not consistent with the standard picture that the cosmic abundance of ^{3}He slowly increases with time due to production by low-mass stars.

Others, including Steigman and his colleagues [18], favor Tytler's low value of primeval deuterium. Then the baryon density is at the high end, $\rho_B \simeq 4.5 \times 10^{-31}\,\mathrm{g\,cm^{-3}}$ or $\Omega_B \simeq 0.02h^{-2}$ (the case for nonbaryonic dark matter is still strong as Ω_B must still be less than 10%). Problems with D and ^{3}He disappear (the small D depletion from the big bang until the present is a little puzzling). However, now ^{7}Li and ^{4}He are problematic. The Spite-plateau abundance is only about half the big-bang prediction and the predicted ^{4}He abundance is $Y_P = 0.245$ compared to the most frequently quoted analysis of the primordial abundance $Y_P = 0.232 \pm 0.003(\mathrm{stat}) \pm 0.005(\mathrm{sys})$ [19]. Accommodating this requires ^{7}Li depletion in old halo stars – there is some observational evidence for depletion [9] and some theoretical models predict depletion [20] – and not taking the errors on the ^{4}He abundance at face value – some have argued that the systematic errors are a factor of two larger [21] and a new determination of the primeval ^{4}He abundance based upon new objects is higher by about 0.01 [22]. (Steigman and his colleagues suggest a more radical solution [23]: new physics in the form of a 10-MeV tau neutrino, which would lead to a reduction in the predicted ^{4}He abundance.)

The quest to pin down the baryon density to 10% and sharply test the big bang with all four light elements is on. A flood of high-quality measurements of light-element abundances

– from deuterium in high redshift clouds to ^{7}Li in halo stars – is rolling in. There is presently some confusion, due to a poor understanding of systematic errors (^{4}He and primeval deuterium) and uncertainty about galactic chemical evolution (^{3}He) and stellar processing (^{3}He and ^{7}Li). I am confident that theory aided by additional observations (or vice versa) will sort things out in the next few years. About the time this happens, there will be a beautiful independent test: A precision determination of the baryon density from the mapping of CBR anisotropy on very small scales (arcminutes to a degree). These measurements will made by balloon-based bolometers, ground-based interferometers and two new satellites (NASA's MAP and ESA's COBRAS/SAMBA). A comparison with the nucleosynthesis determination of the baryon density will be a crucial test of the standard cosmology.

Is the glass half full or half empty? My assessment is half full; not all may agree, but I believe all agree that this is an exciting time.

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